Large amplitude oscillation of magnetization in spin-torque oscillator stabilized by field-like torque

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Oscillation frequency of spin torque oscillator with a perpendicularly magnetized free layer and an in-plane magnetized pinned layer is theoretically investigated by taking into account the field-like torque. It is shown that the field-like torque plays an important role in finding the balance between the energy supplied by the spin torque and the dissipation due to the damping, which results in a steady precession. The validity of the developed theory is confirmed by performing numerical simulations based on the Landau-Lifshitz-Gilbert equation.

Spin torque oscillator (STO) has attracted much attention as a future nanocommunication device because it can produce a large emission power (> 1 μW), a high quality factor (> 10^3), a high oscillation frequency (> 1 GHz), a wide frequency tunability (> 3 GHz), and a narrow linewidth (< 10^2 kHz) [1–9]. In particular, STO with a perpendicularly magnetized free layer and an in-plane magnetized pinned layer has been developed after the discovery of an enhancement of perpendicular anisotropy of CoFeB free layer by attaching MgO capping layer [10–12]. In the following, we focus on this type of STO. We have investigated the oscillation properties of this STO both experimentally [6, 13] and theoretically [14, 15]. An important conclusion derived in these studies was that field-like torque is necessary to excite the self-oscillation in the absence of an external field, nevertheless the field-like torque is typically one to two orders of magnitude smaller than the spin torque [16–18]. We showed this conclusion by performing numerical simulations based on the Landau-Lifshitz-Gilbert (LLG) equation [15].

This paper theoretically proves the reason why the field-like torque is necessary to excite the oscillation by using the energy balance equation [19–27]. An effective energy including the effect of the field-like torque is introduced. It is shown that introducing field-like torque is crucial in finding the energy balance between the spin torque and the damping, and as a result to stabilize a steady precession. A good agreement with the LLG simulation on the current dependence of the oscillation frequency shows the validity of the presented theory.

The system under consideration is schematically shown in Fig. 1 (a). The unit vectors pointing in the magnetization directions of the free and pinned layers are denoted as $\mathbf{m}$ and $\mathbf{p}$, respectively. The z-axis is normal to the film-plane, whereas the x-axis is parallel to the pinned layer magnetization. The current I is positive when electrons flow from the free layer to the pinned layer. The LLG equation of the free layer magnetization $\mathbf{m}$ is

$$\frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m}\times\mathbf{H} - \gamma H_{\rm s}\mathbf{m}\times(\mathbf{p}\times\mathbf{m}) - \gamma\beta H_{\rm s}\mathbf{m}\times\mathbf{p} + \alpha\mathbf{m}\times\frac{d\mathbf{m}}{dt}, \tag{1}$$

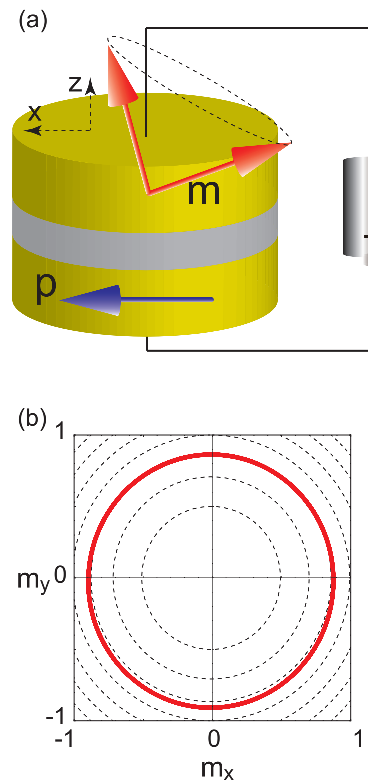

FIG. 1: (a) Schematic view of the system. (b) Schematic views of the contour plot of the effective energy map (dotted), Eq. (2), and precession trajectory in a steady state with $I = 1.6$ mA (solid).

where γ is the gyromagnetic ratio. Since the external field is assumed to be zero throughout this paper, the magnetic field $\mathbf{H} = (H_{\rm K} - 4\pi M)m_z\mathbf{e}_z$ consists of the perpendicular anisotropy field only, where $H_{\rm K}$ and $4\pi M$ are the crystalline and shape anisotropy fields, respectively. Since we are interested in the perpendicularly magnetized free layer, $H_{\rm K}$ should be larger than $4\pi M$. The second and third terms on the right-hand-side of Eq. (1) are the spin torque and field-like torque, respectively. The spin torque strength, $H_{\rm s} = \hbar\eta I/[2e(1+\lambda\mathbf{m}\cdot\mathbf{p})MV]$, includes the saturation magnetization M and volume V of the free layer. The spin polarization of the current and the

dependence of the spin torque strength on the relative angle of the magnetizations are characterized in respective by η and λ [14]. According to Ref. [15], β should be negative to stabilize the self-oscillation. The values of the parameters used in the following calculations are $M = 1448$ emu/c.c., $H_{\rm K} = 20.0$ kOe, $V = \pi \times 60 \times 60 \times 2$ nm^3, $\eta = 0.54$, $\lambda = \eta^2$, $\beta = -0.2$, $\gamma = 1.732 \times 10^7$ rad/(Oe·s), and $\alpha = 0.005$, respectively [6, 15]. The critical current of the magnetization dynamics for $\beta = 0$ is $I_{\rm c} = [4\alpha e M V/(\hbar \eta \lambda)](H_{\rm K} - 4\pi M) \simeq 1.2$ mA, where Ref. [15] shows that the effect of β on the critical current is negligible. When the current magnitude is below the critical current, the magnetization is stabilized at $m_z = 1$.

In the oscillation state, the energy supplied by the spin torque balances the dissipation due to the damping. Usually, the energy is the magnetic energy density defined as $E = -M \int d\mathbf{m} \cdot \mathbf{H}$ [28], which includes the perpendicular anisotropy energy only, $-M(H_{\rm K} - 4\pi M) m_z^2/2$, in the present model. The first term on the right-hand-side of Eq. (1) can be expressed as $-\gamma \mathbf{m} \times [-\partial E/\partial(M\mathbf{m})]$. However, Eq. (1) indicates that an effective energy density,

$$E_{\rm eff} = -\frac{M(H_{\rm K} - 4\pi M)}{2} m_z^2 - \frac{\beta \hbar \eta I}{2e\lambda V} \log\left(1 + \lambda \mathbf{m} \cdot \mathbf{p}\right), \tag{2}$$

should be introduced because the first and third terms on the right-hand-side of Eq. (1) can be summarized as $-\gamma \mathbf{m} \times [-\partial E_{\rm eff}/\partial(M\mathbf{m})]$. Here, we introduce an effective magnetic field $\boldsymbol{\mathcal{H}} = -\partial E_{\rm eff}/\partial(M\mathbf{m}) = (\beta \hbar \eta I/[2e(1 + \lambda m_x) M V], 0, (H_{\rm K} - 4\pi M) m_z)$. Dotted line in Fig. 1 (b) schematically shows the contour plot of the effective energy density $E_{\rm eff}$ projected to the xy-plane, where the constant energy curves slightly shift along the x-axis because the second term in Eq. (2) breaks the axial symmetry of E. Solid line in Fig. 1 (b) shows the precession trajectory of the magnetization in a steady state with $I = 1.6$ mA obtained from the LLG equation. As shown, the magnetization steadily precesses practically on a constant energy curve of $E_{\rm eff}$. Under a given current I, the effective energy density $E_{\rm eff}$ determining the constant energy curve of the stable precession is obtained by the energy balance equation [27]

$$\alpha \mathscr{M}_\alpha(E_{\rm eff}) - \mathscr{M}_{\rm s}(E_{\rm eff}) = 0. \tag{3}$$

In this equation, $\mathscr{M}_\alpha$ and $\mathscr{M}_{\rm s}$, which are proportional to the dissipation due to the damping and energy supplied by the spin torque during a precession on the constant energy curve, are defined as [14, 25–27]

$$\mathscr{M}_\alpha = \gamma^2 \oint dt \left[\boldsymbol{\mathcal{H}}^2 - (\mathbf{m} \cdot \boldsymbol{\mathcal{H}})^2\right], \tag{4}$$

$$\mathscr{M}_{\rm s} = \gamma^2 \oint dt H_{\rm s} \left[\mathbf{p} \cdot \boldsymbol{\mathcal{H}} - (\mathbf{m} \cdot \mathbf{p})(\mathbf{m} \cdot \boldsymbol{\mathcal{H}}) - \alpha \mathbf{p} \cdot (\mathbf{m} \times \boldsymbol{\mathcal{H}})\right]. \tag{5}$$

The oscillation frequency on the constant energy curve

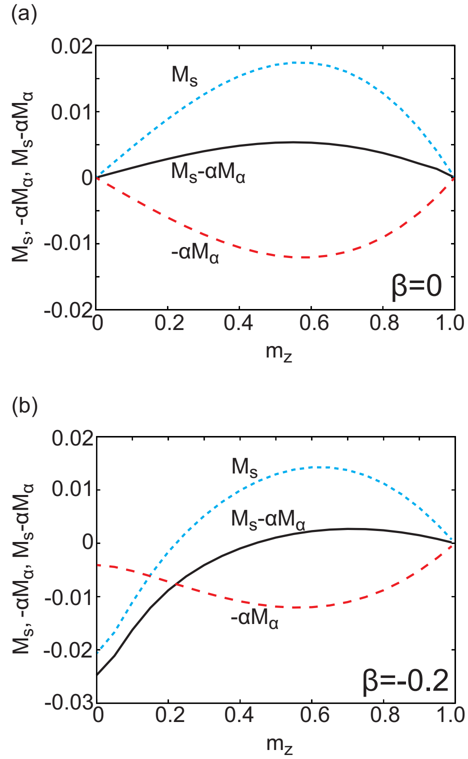

FIG. 2: Dependences of $\mathscr{M}_{\rm s}$, $-\alpha\mathscr{M}_\alpha$, and their difference $\mathscr{M}_{\rm s} - \mathscr{M}_\alpha$ normalized by $\gamma(H_{\rm K} - 4\pi M)$ on m_z ($0 \le m_z < 1$) for (a) $\beta = 0$, and (b) $\beta = -0.2$, where $I = 1.6$ mA.

determined by Eq. (3) is given by

$$f = 1/\oint dt. \tag{6}$$

Since we are interested in zero-field oscillation, and from the fact that the cross section of STO in experiment [6] is circle, we neglect external field $\mathbf{H}_{\rm ext}$ or with in-plane anisotropy field $H_{\rm K}^{\rm in-plane} m_x \mathbf{e}_x$. However, the above formula can be expanded to system with such effects by adding these fields to $\boldsymbol{\mathcal{H}}$ and terms $-M\mathbf{H}_{\rm ext} \cdot \mathbf{m} - M H_{\rm K}^{\rm in-plane} m_x^2/2$ to the effective energy.

In the absence of the field-like torque ($\beta = 0$), i.e., $E_{\rm eff} = E$, there is one-to-one correspondence between the energy density E and m_z. Because an experimentally measurable quantity is the magnetoresistance proportional to $(R_{\rm AP} - R_{\rm P})\max[\mathbf{m} \cdot \mathbf{p}] \propto \max[m_x] = \sqrt{1 - m_z^2}$, it is suitable to calculate Eq. (3) as a function of m_z, instead of E, where $R_{\rm P(AP)}$ is the resistance of STO in the (anti)parallel alignment of the magnetizations. Figure 2 (a) shows dependences of $\mathscr{M}_{\rm s}$, $-\alpha\mathscr{M}_\alpha$, and their difference $\mathscr{M}_{\rm s} - \alpha\mathscr{M}_\alpha$ on m_z ($0 \le m_z < 1$) for $\beta = 0$, where $\mathscr{M}_{\rm s}$ and $\mathscr{M}_\alpha$ are normalized by $\gamma(H_{\rm K} - 4\pi M)$. The current is set as $I = 1.6$ mA ($> I_{\rm c}$). We also show $\mathscr{M}_{\rm s}$, $-\alpha\mathscr{M}_\alpha$, and their difference $\mathscr{M}_{\rm s} - \alpha\mathscr{M}_\alpha$ for $\beta = -0.2$ in Fig. 2 (b), where m_x is set as $m_x = -\sqrt{1 - m_z^2}$. Because $-\alpha\mathscr{M}_\alpha$ is proportional to the dissipation due to the damping, $-\alpha\mathscr{M}_\alpha$ is always $-\alpha\mathscr{M}_\alpha \le 0$. The implications of Figs. 2 (a) and (b) are as follows. In Fig. 2 (a), $\mathscr{M}_{\rm s} - \alpha\mathscr{M}_\alpha$ is always positive. This means that the energy supplied by

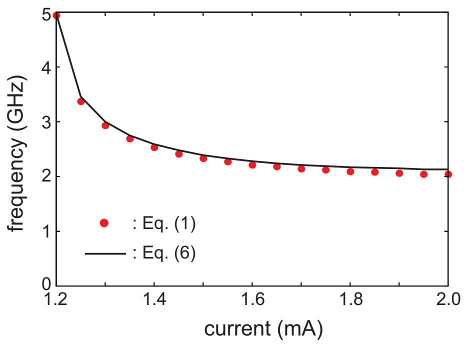

FIG. 3: Current dependences of peak frequency of $|m_x(f)|$ obtained from Eq. (1) (red circle), and the oscillation frequency estimated by using (6) (solid line).

the spin torque is always larger than the dissipation due to the damping, and thus, the net energy absorbed in the free layer is positive. Then, starting from the initial equilibrium state ($m_z = 1$), the free layer magnetization moves to the in-plane $m_z = 0$, as shown in Ref. [14]. On the other hand, in Fig. 2 (b), $\mathscr{M}_{\mathrm{s}} - \alpha\mathscr{M}_{\alpha}$ is positive from $m_z = 1$ to a certain m_z', whereas it is negative from m_z' to $m_z = 0$ ($m_z' \simeq 0.4$ in the case of Fig. 2 (b)). This means that, starting from $m_z = 1$, the magnetization can move to a point m_z' because the net energy absorbed by the free layer is positive, which drives the magnetization dynamics. However, the magnetization cannot move to the film plane ($m_z = 0$) because the dissipation overcomes the energy supplied by the spin torque from $m_z = m_z'$ to $m_z = 0$. Then, a stable and large amplitude precession is realized on a constant energy curve.

We confirm the accuracy of the above formula by comparing the oscillation frequency estimated by Eq. (6) with the numerical solution of the LLG equation, Eq. (1). In Fig. 3, we summarize the peak frequency of $|m_x(f)|$ for $I = 1.2 - 2.0$ mA (solid line), where $m_x(f)$ is the Fourier transformation of $m_x(t)$. We also show the oscillation frequency estimated from Eq. (6) by the dots. A quantitatively good agreement is obtained, guaranteeing the validity of Eq. (6).

In conclusion, we developed a theoretical formula to evaluate the zero-field oscillation frequency of STO in the presence of the field-like torque. Our approach was based on the energy balance equation between the energy supplied by the spin torque and the dissipation due to the damping. An effective energy density was introduced to take into account the effect of the field-like torque. We discussed that introducing field-like torque is necessary to find the energy balance between the spin torque and the damping, which as a result stabilizes a steady precession. The validity of the developed theory was confirmed by performing the numerical simulation, showing a good agreement with the present theory.

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